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Wild harvesting or cultivation of commercial environmental products: A theoretical model and its application to medicinal plants

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ABSTRACT

On average, environmental income accounts for more than a quarter of rural household income in tropical and sub-tropical countries. One way to increase incomes from wild-harvested products is cultivation. In a landmark paper, Homma (1992) identified four phases describing the economic dynamics of environmental product cultivation, emphasising product scarcity. We reviewed literature that applied and/or discussed Homma's model. This suggested that additional factors, beyond resource scarcity, induce the transition to cultivation. We propose an alternative model of the dynamics of environmental product cultivation pathways, emphasising stock size, contextual, harvester, and mediating factors. The model has four possible product-level outcomes: scarcity induced cultivation, economic extinction, abundance with cultivation, and continued sole wild harvesting. We investigated this model empirically through the case of commercial medicinal plant harvesting in Nepal, using harvester interviews ($n = 362$) and published monthly price data for the most commonly traded products ($n = 12$) during a nine-year period. We found evidence of all four possible product-level outcomes, with "abundance with cultivation" being the most common. This supports that scarcity is not sufficient to explain cultivation processes; harvester decision-making processes and contextual and mediating factors must also be assessed.

1. Introduction

Environmental income is important to rural households in developing countries, accounting for an average of 28% of total household income, with the share generally increasing with decreasing household income (Angelsen et al., 2014). Environmental income is "the capture of value added in alienation or consumption of natural capital within the first link in a market chain, starting from the point at which the natural capital is extracted or appropriated" (Sjaastad et al., 2005: 45) and has an equalising effect on local income distributions (Vedeld et al., 2007; Heubach et al., 2011; Chhetri et al., 2015). Across countries, about half of environmental income is cash while the rest is subsistence with cash income associated with greater prosperity (Angelsen et al., 2014). While the rural livelihood literature generally agrees that environmental income is important in preventing poverty (Smith-Hall et al., 2022) through supporting current consumption and occasionally providing gap-filling and safety net functions, the contribution to poverty reduction appears less significant. One of few examples of the latter is the caterpillar fungus *Ophiocordyceps sinensis* in Tibet (Winkler, 2008) and Nepal (Pouliot et al., 2018). Instead, valuable environmental products may enter cultivation processes, with harvesting shifting from wild habitats to agricultural environments. Inspired by Harris (1989) and Larson et al. (2014), we distinguish three modes of production reflecting an increasing input of human energy per unit area. Wild production constitutes the collection of products from species whose reproduction is not directly and actively promoted by humans. Cultivation is the repeated deliberate sowing (including protective tending and transplanting), management, and harvesting of essentially wild plants and seeds, while domestication is the cultivation of genetically altered species, e.g. through artificial selection, that display phenotypic characteristics distinguishing them from wild progenitors. Examples of environmental products with a relatively narrow geographical origin that have become common agricultural products with high economic value include vanilla (*Vanilla planifolia*), first domesticated in south-eastern Mexico (Cameron, 2011) and the Arabica coffee (*Coffea arabica*) from south-eastern Ethiopia (Davis et al., 2012). However, most environmental products remain wild-harvested, e.g. of the more than 28,000 plant species mentioned in official pharmacopoeia (Willis, 2017), only a little more than 3200 species are in cultivation for commercial production (Brinckmann et al., 2022). Some environmental

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products are both cultivated and wild harvested, e.g. the widely traded Himalayan herb *Swertia chirayita* (Cunningham et al., 2018b).

In a landmark paper, Homma (1992) identified four phases describing the economic dynamics of environmental product cultivation. See Appendix A for Homma's graphical illustration of the four phases. This model emphasises increasing resource scarcity as the driver of price changes, leading to three possible outcomes: (i) a shift from wild harvesting to cultivation, (ii) overexploitation, economic extinction, and disappearance of the product, or (iii) product substitution and decreased wild harvesting. Wild harvesting increases in the initial expansion phase due to exogenous changes such as improved extraction techniques or infrastructural developments. A contemporary example of this is the expansion of road infrastructure in the hills and mountains of Nepal, e.g. opening up new populations of *Bergenia ciliata* to commercial harvesting in the far-western part of the country (Pyakurel et al., 2018). The second phase is a period of stabilisation with supply equalling demand close to the maximum extractable amount. Belcher et al. (2000) suggested Brazil nut (*Bertholletia excelsa*) as an example; however, there are no documented cases of this phase in the literature, reflecting low interest in the study of stable products, that the phase is too short to observe it empirically, or that the stable price is distorted by other factors. In the third phase, the decline phase, prices increase when growing demand cannot be met as supply is inelastic; the quantity and quality of naturally occurring products decrease, and cultivation is initiated if this can lower production costs and increase land and labour productivity. In Lao PDR, the agarwood (*Aquilaria* spp.) extraction entered this decline phase without becoming cultivated due to lack of technology (Jensen, 2009) while paper mulberry (*Broussonetia papyrifera*) was successfully cultivated by local people (Neef et al., 2010). A product can enter the fourth phase, the cultivation phase, if the required technology is available, substitutes do not exist, and prices remain high. Examples include the above-mentioned vanilla and coffee.

While Homma's model of environmental product cultivation has been widely cited ($n = 410$ for the two papers mentioned in section 2.1), it has not been systematically reviewed in its three decades of existence. Explaining why some species are selected for adaptation to human agro-ecological niches while others continue to be wild-harvested can help focus future cultivation efforts on the benefits to rural households, local and national economies, international consumers, and species conservation. The importance of environmental products in the income of rural households in lower income countries and wild harvesting conservation concerns led us to draw together and test current knowledge to create an up-to-date understanding of the economic dynamics of environmental product cultivation. Specifically, we (i) systematically review studies related to Homma's model, (ii) use the results to develop a new/revised theoretical model, and (iii) apply the model to the case of commercial medicinal plants harvested in Nepal.

2. Methods

2.1. Literature review

Following the review approach by Myers and Hansen (2020), we analysed all references (as of 12 August 2020) that cited "The Dynamics of Extraction in Amazonia: A Historical Perspective" (Homma, 1992) and/or the revised version "Modernisation and Technological Dualism in the Extractive Economy in Amazonia" (Homma, 1996). We used "cited by" in Google Scholar to identify the 410 publications citing the two references (Fig. 1). Counting papers that cited both papers only once, the preliminary total was 384 publications. Of these, we found 337 available for review: they could be located, downloaded, and were not the same publication published in different forms (36); 11 references could not be accessed. We included publications in all languages and forms, including books and book chapters, journal articles, conference papers, working papers, masters and PhD theses, and grey material.

For each publication, we assessed the intensity of use of Homma's model: 1 = low, cited only or made a cursory reference to some aspect of the model; 2 = medium, used in analysis, e.g. assigning species to one of the four phases; and 3 = high, providing an explicit discussion of the model. High-intensity publications (marked with * in references) were all analysed for what aspects of the model they built upon and/or critiqued, and what bodies of literature they based their contribution on.

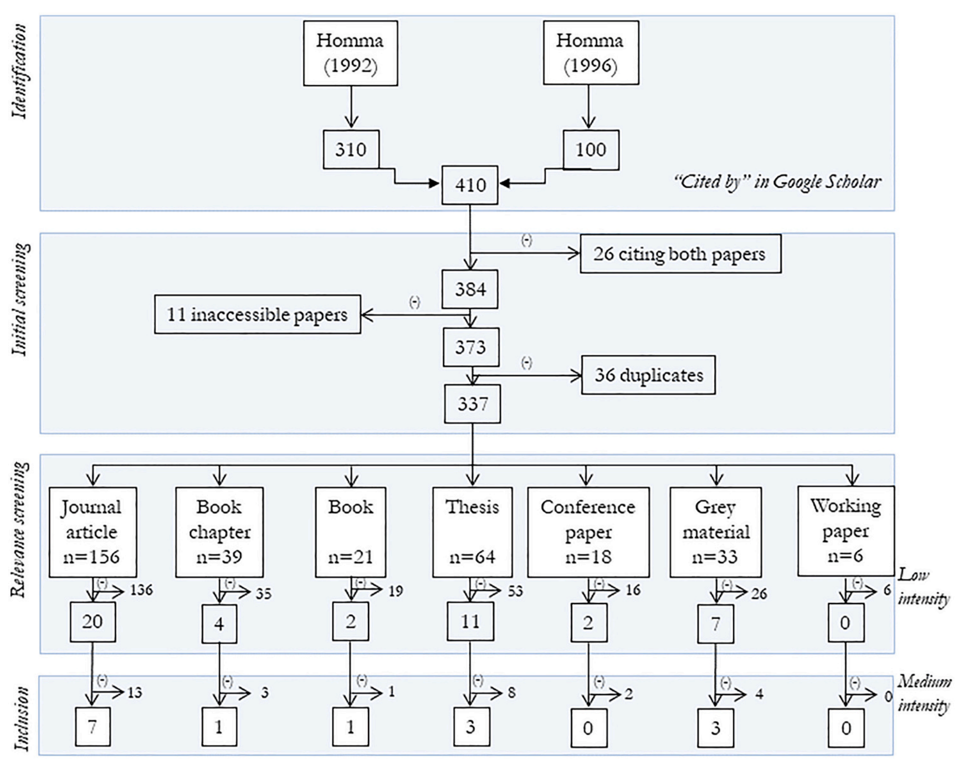


Fig. 1. Diagram of steps to identify, screen, and include documents in the literature review.

Low and medium intensity publications were not explored further. The synthesis of the high-intensity references was used to draw up the revised model.

2.2. Study area

Data for the empirical analysis were collected in Nepal (26° 20′–30° 35′ N latitude, 80° 05′–88° 10′ E longitude, 60–8848 m a.s.l., 147,181 km^2). In 2017, 80.7% of the country's population lived in rural areas (World Bank, 2019). The climate ranges from tropical in the country's southern parts (the Terai) to alpine in the northern parts. Fig. 2 illustrates the development regions, the physiographic zones, and the 15 fieldwork districts. Recently, Nepal became a federal republic organised into seven provinces (one of which is not yet named).

2.3. Product selection

The empirical data collection focused on commercial medicinal plants, fungi, and lichens in Nepal. This trade includes up to 300 products (Pyakurel et al., 2019) produced from the southern lowlands to the northern high mountains, air-dried and exported to mainly India and China where secondary processing is undertaken (Smith-Hall et al., 2020). Modes of production range from active cultivation to wild harvesting. The large number of products produced in different ways, but traded in the same production network, allowed variation in species-level data (cultivated or not) and cost-efficient data collection (many harvesters encountered in the same production network). An overview of the commercial raw products provided by each species (e.g., seeds, or barks) is provided in Pyakurel et al. (2019). Species names follow Bisby et al. (2010).

2.4. Data collection

As part of a larger research project on medicinal plant trade, data on medicinal plant harvesters (whether wild harvesting or cultivating) were collected in 15 districts using structured questionnaires. Districts were randomly selected within each of the 15 cells formed by the combination of physiographic zones and development regions (Fig. 2). The complete data collection instrument is available in Smith-Hall et al. (2018); it included questions on harvester characteristics, the origin of harvests, and associated costs. Data were collected for the Nepalese year 2071 (2014–15) in 2015–16. Respondents were snowball sampled en route. In total, 362 harvesters were interviewed, yielding 553 observations relating to 44 different products.

To analyse product-level price changes over time, we collected monthly central wholesaler prices (paid by central wholesalers to traders) from 2010 to end-2018 for the 12 most frequently harvester reported (n ranging from 12 to 79) medicinal plants. This excluded kakoli (*Fritillaria cirrhosa*, $n = 30$), kauolo (*Machilus odoratissima*, $n = 19$), and yarsagumba (*Ophiocordyceps sinensis*, $n = 61$) for which price data were unavailable. The data were obtained from the Asian Network for Sustainable Agriculture and Bioresources and covered Kathmandu and Nepalgunj, the former supplied by the Herbal Entrepreneurs Association of Nepal and the latter by the Jadibuti Association of Nepal. Prices were adjusted for inflation using the monthly consumer price index (IMF, 2018) (December 2014 indexed 100), converted to USD (IMF, 2014), and PPP-adjusted (World Bank, 2020).

2.5. Data analysis

Following the development of the revised model, we estimated the effect of harvester and geographical characteristics on the likelihood of cultivation using a probit model with the latent variable model:

$$y^* = \beta_0 + \beta_1 female + \beta_2 age + \beta_3 wealth\_above\_avg + \beta_4 avg\_wealth + \beta_5 formal\_educ + \beta_6 terai + \beta_7 mountain + \beta_8 protection + \beta_9 several\_products + \beta_{10} only\_low\_value + \beta_{11} only\_high\_value + e$$

where the error term, e, is normally distributed, $e \sim N(0,1)$. The relationship between the observed variable and the latent variable y^* is described by the indicator function, $cultivate = 1[y^* > 0]$, taking the value 1 if the harvester cultivates at least one product. An overview of expected effects is given in Table 1. The average partial effects (APE) for each explanatory variable are reported, showing, e.g., the average change in the likelihood (between zero and one) of cultivating at least one product when age (seen in Table 1) increases by one year across all

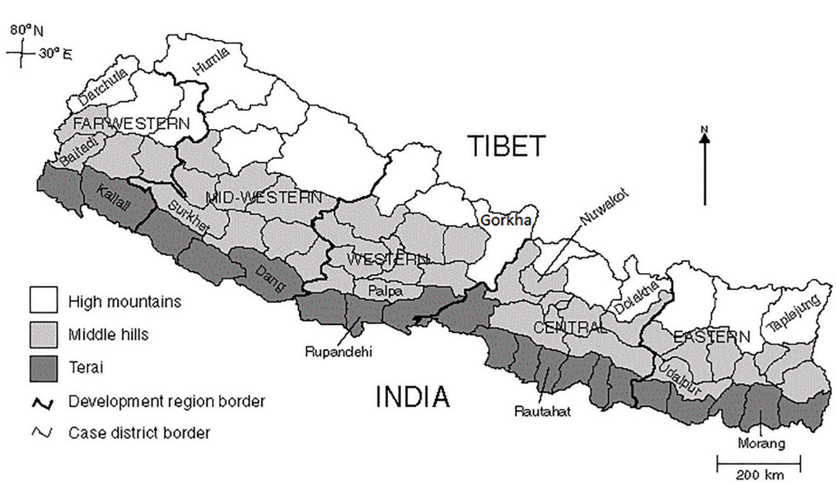


Fig. 2. Fieldwork districts (small letters), physiographic zones (shaded, north to south), and development regions (capital letters, west to east). Source: Smith-Hall et al. (2018).

Table 1
Overview of the expected relationships between harvester and geographical characteristics and medicinal plant cultivation in Nepal.

Variable	Effect	Hypothesis
Age	+	Young harvesters engage more in wild harvesting as a non-prestigious activity; older harvesters with other options choose these (Larsen and Smith, 2004) including cultivation.
Female	−	Male is the base category. Female-dominated households are more dependent on income from wild-harvested environmental plants (Quang and Anh, 2006, Heubach et al., 2011), hence less likely to cultivate.
Wealth above avg.	+	Below average wealth is the base category. Wealthier households are less willing to practice wild harvesting (Larsen and Smith, 2004). Land ownership is an omitted variable but positively correlated with wealth (Rayamajhi et al., 2012).
Avg. wealth	+	Follows reasoning above.
Formal education	+	No formal education is the base category. Higher education is associated with lower reliance on environmental income, and better remunerative activities (Rayamajhi et al., 2012) hence educated people are expected to be more likely to cultivate.
Terai	−	Middle Hills is the base category. Medicinal plant species richness is lower and cultivation less common in the Terai than in the Middle Hills (Pyakurel et al., 2019).
Mountain	−	More abundant medicinal plant resources in the Mountains than in the Middle Hills create less pressure for cultivation (Pyakurel et al., 2019).
Protected species	−	Harvest of no protected species is the base category. Protected species as per Smith-Hall et al. (2020). Protection includes bans on collection, trade, or export by the Government of Nepal and Appendix II listing by CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora). Protected species are expected to be less likely to be cultivated due to trade restrictions.
Several products	−	Harvesting only one product is the base category. Cultivators are expected to specialize in fewer species while wild-harvesters harvest all species they find with satisfactory return.
Only low-value products	+	Harvesting of products of medium value or differing values across products is the base category. Value as per Smith-Hall et al. (2020). Per unit low-value products are mainly associated with cultivation; a decline in value after cultivation is expected.
Only high-value products	−	Per unit high-value products are expected mainly to be those that are not cultivated yet.

harvesters.

The distribution between those who only wild harvest and those who also cultivate is fairly equal (Table 2). The regression above is also run where observations of harvesters of yarsagumba, a high-value product that has contributed to large economic transformations (Smith-Hall and Bennike, 2022), are excluded. Because yarsagumba is widely harvested in the survey sample and expected to be closely correlated with more of the explanatory variables (e.g. Mountain and only high-value products), we are interested in confirming that identified relationships hold when yarsagumba harvesters are excluded. Only one yarsagumba harvester cultivated another species, making the distribution more skewed (Table 2).

3. Results

3.1. Reviewing the Homma (1992, 1996) model

The underlying assumptions regarding household behaviour and decision making (Almeida, 1996) and the theoretical understanding of environmental product cultivation processes need to be tested or developed further (Newton et al., 2006). The literature on Homma's (1992, 1996) model can be categorised into three main areas of work:

1) Additional factors influencing the transition from wild harvesting to cultivation identified from empirical research.
2) Discussions of the limitations of the model's explanatory power and suggestions to modify the model.
3) Discussions of the applicability of the unidirectional development that the model builds upon.

Re 1: Empirical studies on Homma's model have suggested various additional influencing factors. In Lao PDR, Ribeiro and Darnhofer (2007) found that time optimisation rather than scarcity of the wild resource was the driver of paper mulberry tree cultivation. Harvesters were aware of their opportunity cost of harvesting the product; though importers of the bark showed a keen interest in increasing the supply, harvesters often found the price too low to initiate cultivation. In Bolivia, legal bans and successful campaigning by environmental NGOs have led to the collapse of trade in hides and skins of forest animals rather than overexploitation (Stoian, 2000). A study from South Africa found that harvesters did not initiate cultivation of any of the six species investigated despite demand and price increase (Shackleton, 2005). Either a product remained abundant, habitat requirements were too specific, or restrictive land and water accessibility made the products impossible to cultivate.

Table 2
Numbers of harvester observations.

	Wild harvesting	Cultivation (and wild harvesting)	Total
All observations	173	184	357
Observations excl. yarsagumba harvesters	114	183	297

Other researchers argued that cultivation initiation is primarily a response to demand rather than scarcity of species (Shinwari, 2010), e.g. cultivation of *S. chirayita* and *Zanthoxylum armatum* were initiated to meet commercial demand (Hertog and Wiersum, 2000; Cunningham et al., 2018b). Thus, it is not possible to use price directly as an indicator of scarcity (Cunningham and Long, 2019), as implied by Homma's model. Though scarcity has stimulated the cultivation of *P. polyphylla* and artificial production of *O. sinensis*, it has not reduced pressure on wild populations yet, and the price of *P. polyphylla* continues to increase (Cunningham and Long, 2019).

Re 2: Other papers have suggested model improvements that include accounting for interactions between the markets for related environmental products, moving beyond the narrow focus on the cycles of individual environmental products. After the rubber collapse in the Bolivian Amazon between 1946 and 1973, harvesting of other wild species flourished (Stoian, 2000). An increase in trade in one species often increases the abundance of substitutable or economically inferior species as harvesters concentrate labour on species with the highest demand (Wilkie and Godoy, 1996), e.g. the high price of *O. sinensis* may pull harvesters from collecting less remunerative species (Smith-Hall and Bennike, 2022). If the value of certain environmental products rises, the increase in the opportunity cost of labour and land will reduce the number of species harvested as harvesters allocate their time on the more valuable species, leading to specialization and cultivation (Wilkie and Godoy, 1996).

Land tenure and management are other important aspects explaining the harvesting mode. Habitat conversion occurring concurrently with high level of wild harvesting increases the risk of extinction above the risk associated with each action separately (Newton, 2008). From an economic perspective, areas with environmental products of value would be expected to be less likely to be converted to agriculture, but for eight species across Asia and America, the value did not prevent habitat conversion (Newton, 2008). Furthermore, according to Belcher et al. (2000), there are undescribed conditions in Homma's model that encourage intermediate systems, i.e. modes of production on the continuum from pure wild harvesting to intensive domestication. These range from weeding around valuable species to transplanting of wild plants to optimal areas. Changes from collective to individual land rights encourage intermediate systems (Belcher et al., 2000). In Homma's model, intermediate systems would be a stage in a process towards cultivation, but intermediary systems might not only be temporary (Belcher et al., 2000).

Certain types of households drive the transition from wild harvesting to cultivation. Belcher et al. (2005) found specialization to be a consequence of price increases and associated with either more intensive management, which is only possible for wealthier households, or harvesting from a larger area, which is only possible in remote areas. Poor people are more likely to lack land tenure security, confidence in the market, and economic security as they await the yields of cultivation (Belcher et al., 2005). If harvesters' access to infrastructure is poor and transportation costs are high, cultivation will only be feasible for high value products (Wilkie and Godoy, 1996).

Re 3: Several studies have discussed whether the reality of environmental product exploitation and cultivation is too complex to fit into a unidirectional model. Newton et al. (2006) argued that Homma's model is too conceptual, qualitative, and deterministic to be applicable to the complex contexts of environmental product trade. Goeschl and Igliori (2004) proposed an analytical framework to examine whether Homma's stages are inescapable and concluded that the economic cycle proposed by Homma need not lead to extinction of the wild occurrence of the species. This is supported by Arnold and Pérez (2001), who further suggested that institutional measures can modify the impact of wild harvesting, e.g. by increasing productivity of the wild resource rather than cultivation. An empirical example of the more complex reality is the Bolivian palm heart industry, which was initiated in the 1960s, closed down shortly after, reopened in the 1990s, and closed down again before it led to plantation programs as predicted by Homma's model (Stoian, 2000).

3.2. *Beyond Homma – Additional information on wild harvesting vs. cultivation and the prices*

Though not directly relating the point to Homma's model, Godoy and Bawa (1993) discussed that poor harvesters harvest small amounts of many low-value wild products, while richer harvesters harvest fewer of higher value and fewer wild products (Godoy and Bawa, 1993). Angelsen et al. (2014) empirically documented the propensity for wealthier households to generate higher environmental income. Cultivated products compete against wild products where labour is the only input (Schippmann et al., 2002). As the opportunity cost of labour increases with emerging job opportunities, the cost of wild harvesting increases, and harvesters focus on more valuable products (Godoy and Bawa, 1993). Spatial arbitrage opportunities, as found for commercial medicinal plants in Nepal (Olsen and Helles, 2009), provide differentiated incentives for harvesters to cultivate. The end-use might increase harvesting intensity through higher export (Godoy and Bawa, 1993) or domestic prices (Paudel and Smith-Hall, 2022).

Consumers may be willing to pay more for wild products (Schippmann et al., 2002), e.g. as they associate *O. sinensis* with the unpolluted landscape, imbuing the product with health benefits (He et al., 2022). Other reasons for price spikes or drops are: capital flows into the specific market, information (potentially incorrect) regarding cultivation, general demand for environmental products, traders' expectations of market size, monetary policies, financial crises, abnormal climatic events, policies to combat corruption, human disease outbreaks, previous year's stock and price, and harvesters' risk attitude (Cunningham and Long, 2019).

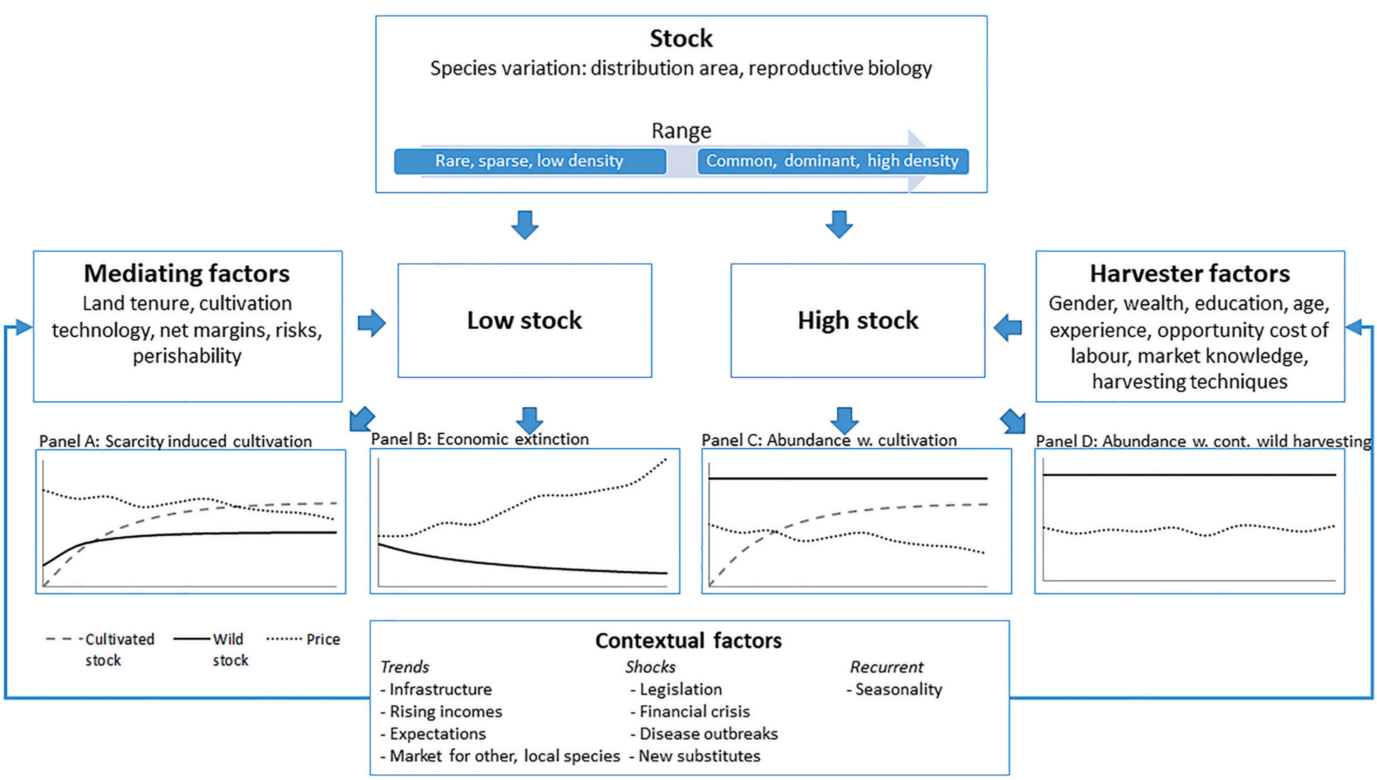


Fig. 3. The dynamics of environmental product cultivation pathways, panels A-D. Harvester, mediating, and contextual factors influence individual species stock, whether a species is cultivated or not, and price development. In each panel, the y-axis is quantity or price, and the x-axis is time.

3.3. A new model for environmental product cultivation pathways

Figure 3 builds on the above literature review to propose possible pathways to environmental product cultivation, including the determining factors and the resultant outcomes in terms of stock changes and price development. The model takes a point of departure in the naturally occurring stock, i.e. the number of resource-producing individuals for a particular species. The stock is determined by distribution area, influenced by bioclimatic and topographical factors, land use conversion processes, and a species' reproductive biology. It can range from sparse and low density to abundant and high density.

The stock is changed by harvesting, influenced by yield, the mode of harvesting (e.g., destructive or not, timing in relation to reproduction), and harvesting intensity. For clarity, the model distinguishes between species-level small and large stock situations. Contextual factors reflecting (e.g., market expectations) and restricting (e.g., legislation) demand and affecting costs (e.g., through changes in infrastructure) modify harvesters' behaviour and the mediating factors determining whether cultivation is undertaken or not. Harvester characteristics (age, education, etc.) influence their propensity to cultivate while the mediating factors (technology, land tenure, etc.) influence the viability of cultivation. Contextual factors encompass trends, shocks, and recurrent factors. Trends include infrastructural developments (e.g., road and telecommunication) and rising incomes in consumer markets. Shocks are sudden changes influencing demand or supply and thus prices. Recurrent events include the seasonality of product availability and livelihood strategies.

The species-level interplay of the contextual, mediating, and harvester factors with available stock in a particular location result in cultivation and/or continued wild harvesting and the associated price developments (panels A-D):

A. Scarcity induced cultivation: the scenario where a small stock (threatened) and continued demand leads to cultivation. This increases supplies from cultivation, with the decreasing price leading to a recovery of the naturally existing stock and an overall stock increase in accordance with Homma's (1992) predictions.
B. Economic extinction: the scenario where a small stock does not induce cultivation, e.g. due to lack of (existing) technology, challenges imposed by a species biology including habitat requirements, availability of cheap and close substitutes (e.g. synthetic), or more remunerative alternative income sources (e.g. cultivation of other species or agricultural crops). This leads to increasing prices, a further decreasing stock, and economic extinction through high-value resource mining or medium-value unmanaged over-exploitation (Swanson, 1994).
C. Abundance with cultivation: the scenario where cultivation is initiated despite a large stock. The cultivation will leave the pre-existing wild stock unchanged or increased depending on plant population dynamics. Cultivation will reduce a relatively low price further. Such cultivation can be initiated to reduce opportunity costs, respond to demand changes more easily, and increase productivity, influenced by access to land and income from competing agricultural crops and environmental products. It may also occur where local plant populations are declining, leading people in a specific area to cultivate despite no overall threat to the species.
D. Abundance with continued sole wild harvesting: the scenario where a large naturally occurring stock does not initiate any cultivation as predicted by Homma's (1992) model. If harvesting does not exceed the yield, the stock will not diminish (though this could happen locally). The price for such products will fluctuate around a low mean price.

Environmental product cultivation pathways are dynamic. For instance, a wild harvested threatened plant species heading towards economic extinction (panel B) might go into scarcity induced cultivation due to technological advancements (panel A).

Table 3
Relationships between harvester ($n = 362$) and geographical characteristics, and medicinal plant cultivation (dependent variable) in Nepal, 2014–15.

	All observations		Excluding yarsagumba harvesters	
	Estimate	APE	Estimate	APE
Age	0.0182*	0.0036*	0.0180*	0.0042*
	(0.0082)	(0.0016)	(0.0084)	(0.0019)
Female	−0.4945*	−0.0996*	−0.5596*	−0.1341*
	(0.2237)	(0.0452)	(0.2272)	(0.0551)
Wealth above avg.	0.9609***	0.1813***	1.0508***	0.2237***
	(0.2845)	(0.0486)	(0.2935)	(0.0530)
Avg. wealth	0.7908***	0.1573***	0.8028***	0.1864***
	(0.2217)	(0.0424)	(0.2197)	(0.0485)
Formal education	0.0677	0.0133	0.1085	0.0253
	(0.1952)	(0.0389)	(0.1964)	(0.0462)
Terai	−0.4974	−0.0934	−0.4365	−0.0981
	(0.2767)	(0.0485)	(0.2770)	(0.0595)
Mountain	−1.5381***	−0.4048***	−1.4151***	−0.4028***
	(0.2490)	(0.0682)	(0.2497)	(0.0700)
Protected species	−0.1970	−0.0395	−0.2602	−0.0618
	(0.2353)	(0.0477)	(0.2453)	(0.0595)
Several products	0.0603	0.0119	0.0314	0.0073
	(0.1921)	(0.0379)	(0.1941)	(0.0447)
Only low value	0.2674	0.0550	0.2906	0.0693
	(0.2971)	(0.0633)	(0.2988)	(0.0730)
Only high value	−1.8048***	−0.4410***	−1.2717***	−0.3327***
	(0.3205)	(0.0698)	(0.3606)	(0.0930)
Constant	0.0418		0.0135	
	(0.5172)		(0.5211)	
Log-likelihood	−123.8		−121.4	
Pseudo R-squared	0.4909		0.3863	
Squared correlation	0.5606		0.4589	
Correct predictions (%), total;0;1	83.5; 85.0; 82.1		80.5; 75.4; 83.6	

Average partial effects (APEs) in columns three and five. Standard errors in parenthesis. Significance codes: *** significance at the 0.1% significance level, ** significance at the 1% significance level, and * significance at the 5% significance level.

3.4. Applying the model: commercial medicinal plants in Nepal

Factors that determine whether a harvester engages in cultivation and the species-level price dynamics were investigated.

3.4.1. Cultivation pathways: who cultivates commercial medicinal plants in Nepal?

A strong and positive relationship between household wealth and the likelihood of cultivating was found (Table 3). The dependent variable, cultivation, is binary and takes the value 1 if the harvester cultivates at least one product (see section 2.5). Cultivation was on average 10 percentage points less likely when the harvester was female while the likelihood of cultivation increased by on average 0.4 percentage points for each year of age of the harvester (Table 3). The only unexpected (but insignificant) sign, implying that multiple-product harvesters were more likely to engage in cultivation, might be influenced by that several of the harvesters who cultivate also wild harvest. The relationship between cultivation and high-value products was strong and negative, showing that harvesting only high value products reduced the likelihood of

Table 4
Number of species in each category observed in the current study.

	Wild harvested	Cultivated	Both
Protected species	5	1	2
Not protected species	2	3	4

Includes species with more than eight harvester observations. "Both" includes species where <90% of observations fall in either of the other categories.

cultivation by on average 44 percentage points (Table 3). The relationship was not solely driven by yarsagumba harvesters (who wild harvest) as removing these observations only reduced the magnitude of the effect to 33 percentage points (Table 3). Being a harvester in a mountain district reduced the likelihood of cultivating by 40 percentage points compared to in a hill district; this is not surprising as forests and other wild habitats are abundant while the conditions for agriculture are limited. Variables maintain their original magnitude and significance when observations of yarsagumba harvesters are removed. The explanatory variables do not suffer from multicollinearity (VIF < 2.0 for any variable).

Harvesting a protected species had a weak and insignificant tendency to reduce the likelihood of cultivation. Wild harvested species were more often protected (Table 4). The reason that more non-protected species were cultivated may reflect a past focus on developing cultivation technology for lowland species (Pyakurel et al., 2019).

3.4.2. *Species-level cultivation pathways: Learning from commercial medicinal plant prices in Nepal*

We used average central wholesaler prices to empirically investigate species-level cultivation pathways, Fig. 4a-l.

Chiraito (panel 4b) and kurilo (4f) arguably are examples of panel 3A (scarcity induced cultivation). Increased chiraito demand in India in the early 1990s led to higher prices in Nepal (DeCoursey, 1994) with subsequent intensive harvesting leading to scarcity, diminishing wild populations, and cultivation on agricultural land (Phoboo and Jha, 2010). Increased supplies could explain the price decrease from 2013. Chiraito is considered vulnerable in Nepal (Pyakurel et al., 2017) and critically endangered in northern India (Cunningham et al., 2018b). The low price implies low profitability from cultivation that is no longer expanding (Cunningham et al., 2018b). Likewise, kurilo (4f) is both cultivated and wild harvested, and vulnerable (Smith-Hall et al., 2020).

The prices of the solely wild harvested satuwa (panel 4j) and jatamansi (4e) have increased overall during the period. The species are relatively slow growing: satuwa rhizomes take 7–8 years to mature leading to immature harvesting (Chauhan et al., 2018), and the slow growth of jatamansi might prevent harvesters from engaging in cultivation (Rai et al., 2000). Both products are overharvested in some locations (Paul et al., 2015; Pyakurel et al., 2017; Chauhan, 2021) and at risk of local extinction. Based on the price increase, the vulnerability of the products (dwindling stocks), and the wild harvesting, satuwa and jatamansi are examples of panel 3B (moving towards economic extinction).

The largest number of products has some fit with panel 3C (abundance with cultivation). The species are the widely distributed and cultivated amala (4a), ritha (4i), tejpat (4k), and dalchini (4c) with low per unit prices that tend to decline though there are fluctuations. The harvesting of timur (4l) is mainly driven by demand rather than scarcity (Hertog and Wiersum, 2000; Pyakurel et al., 2017). Timur is not protected, and widely cultivated, suggesting that timur is also a case of abundance with cultivation, despite the upward price trend. The product is slow-growing (Kala et al., 2005) and if demand is increasing, this could explain the price trend. While in the literature, nirmasi (4h) has only been found to be wild harvested (Smith-Hall et al., 2020), the current harvester survey showed that the species is now also cultivated, and price data revealed a high, but declining, price in recent years which may indicate that this product is transiting from panel 3B to 3C.

Two products have some fit with panel 3D (abundance with continued sole wild harvesting). Kutki (4g) occurs throughout high-altitude areas in the country and cultivation is limited to trials (Poudeyal et al., 2021). The species has a rapid recovery rate and is less sensitive to commercial harvesting than other high-altitude species (Ghimire et al., 2005). However, the species has been assessed as vulnerable and cannot in principle be exported without certification. Guchhichyau (morels, 4d) is also widespread, uncultivated, and unprotected. However, guchhichyau is characterised by its high price indicating a possible special fungi situation: while culinary demand and prices are high, complex but poorly understood reproduction strategies (Pilz, 2007) could act to make natural populations resilient to collection, enabling continued wild harvesting at high prices without negatively affecting fungi populations.

4. Discussion

The literature review suggested that Homma's (1992, 1996) model, with its focus on four distinct phases and increasing resource scarcity as the driver of price changes, is too narrow to explain empirically observed processes of environmental product cultivation. Our model emphasises the potential roles of harvester, mediating, and contextual factors. Factors can be characterised by their type (general, location specific, or species specific) and mode of operation (direct, indirect). Type examples include: (i) general factors: the Belt and Road Initiative seeking to roll out Traditional Chinese Medicine, increasing demand for a number of species; (ii) location specific factors: new legislation such as promoting community-based resource management in a country, or improved district-level infrastructure such as a road decreasing transportation costs; (iii) species specific: new technology such as seedling production or interventions such as harvesting and trade bans. Mode of operation examples include: (i) direct: reduced royalty rate making trade more profitable, and (ii) indirect: more off-farm income opportunities reducing labour available for wild harvesting.

Four findings based on the Nepalese case and supported by results from other countries stand out in relation to the revised model:

1. To understand pathways and design sustainable interventions to the benefit of harvesters and species, it is necessary to pay attention to the interactions between species biology and demand-side issues. For instance, increasing demand has led to overexploitation of satuwa in India (Vidyarthi et al., 2013) and cultivation of chiraito in Nepal (DeCoursey, 1994). The former is a slow growing herbaceous understory perennial, with low flowering and seed germination frequency (Cunningham et al., 2018a) and rhizomes taking 7–8 years to mature (Chauhan et al., 2018) compared with the 1–3 years required for a chiraito whole-plant crop using available cultivation technology (Cunningham et al., 2018b). Despite the large-scale trade in commercial medicinal plants from Nepal, not a single species or product has been subjected to detailed consumer surveys, and hence the demand drivers remain unknown.
2. A low stock and a rising product price do not necessarily lead to cultivation, or it might take time (panel 3B). Both jatamansi and satuwa are characterised by intense wild harvesting and increasing prices while no cultivating activities have been undertaken despite unsustainable harvest (Paul et al., 2015; Pyakurel et al., 2017; Chauhan, 2021). Similarly, studies in Benin and Ghana showed that despite overharvesting and extensive commercialisation of *Securidaca longipedunculata* and *Piper guineense*, cultivation did not occur or was rare (Van Andel et al., 2015). A study in Sumatra found that only one product (*Daemonorops draco*) entered cultivation in response to declining wild resources (Schmidt et al., 2020). While our model includes potential explanations for these outcomes, the substantial price changes that some products show require market understanding to explain. Fluctuating prices are common, e.g., for *O. sinensis* and *Schisandra sphenanthera* in China (Cunningham and Long, 2019). Empirical investigation could clarify whether the model's contextual factors are exhaustive in explaining fluctuations.
3. Our Nepalese case further showed that species not subject to overexploitation often are cultivated, despite relatively low prices (panel 3D). The emphasis in the literature on overexploitation as the main driver of cultivation could indicate a research bias towards endangered species; our study purposefully asked harvesters about all traded species.

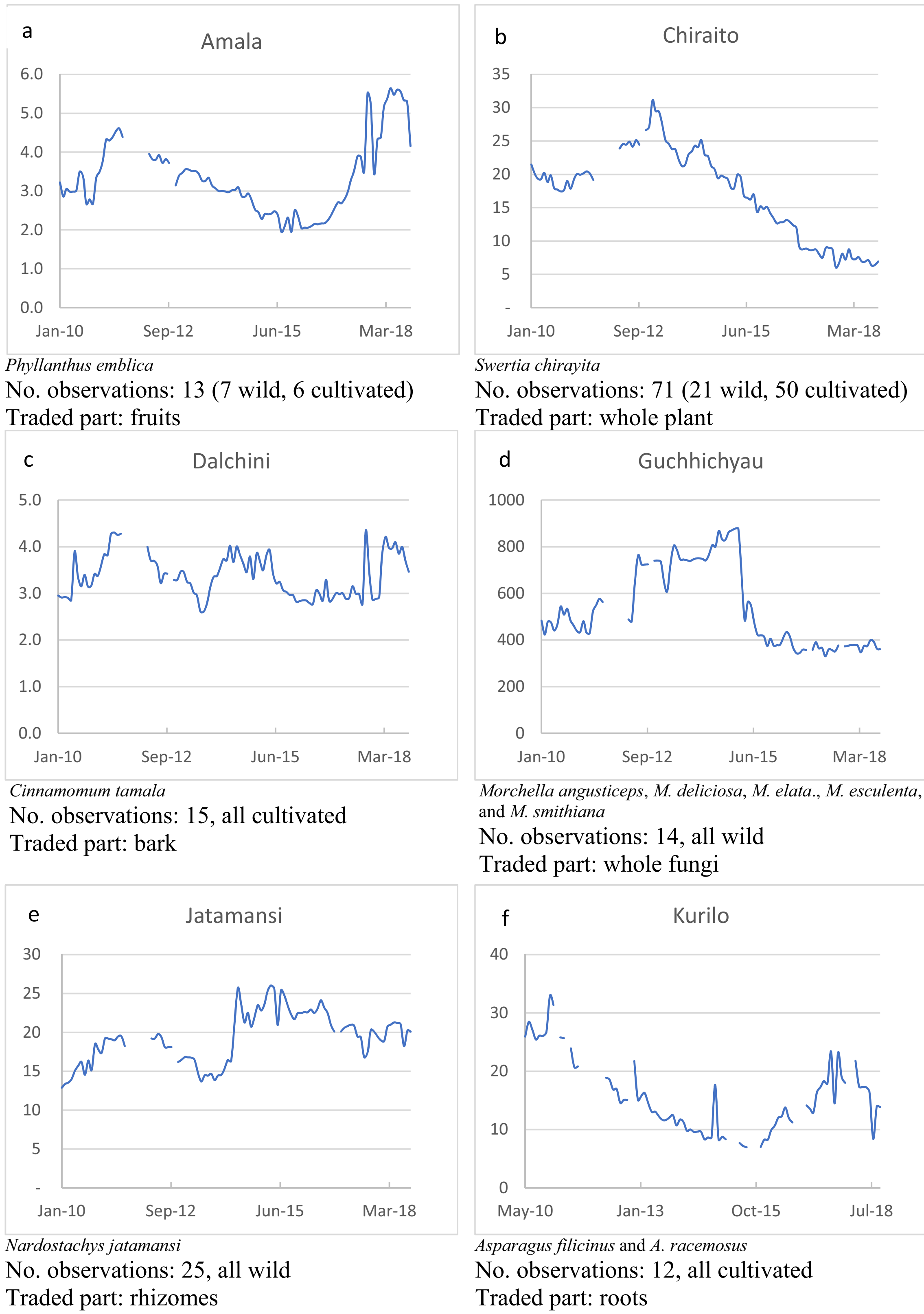
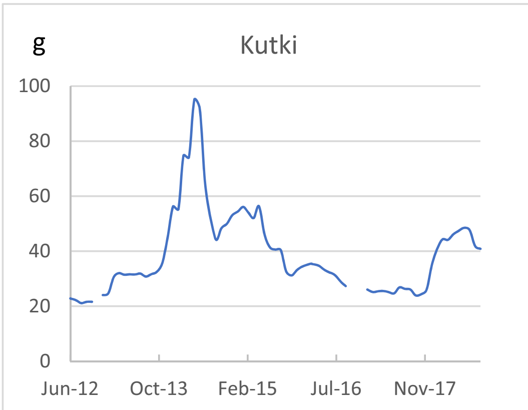
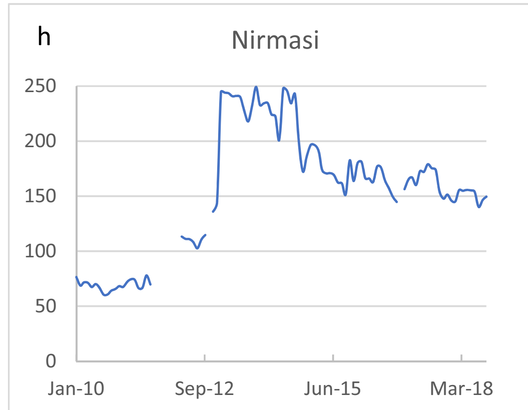


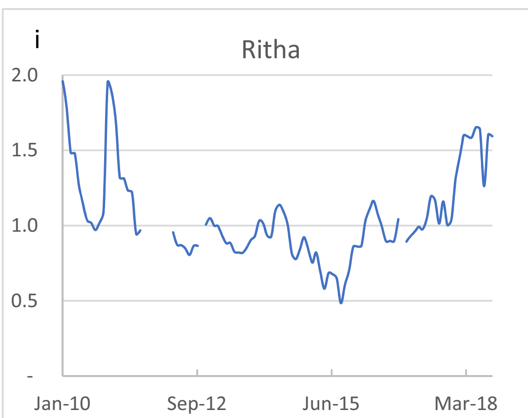
Fig. 4a-. l. Average central wholesaler price (in 2014 USD PPP) for 12 commercial medicinal plant products harvested in Nepal, 2010–2018. Common trade name at top of each panel, scientific name below. Numbers of observations are from the harvester survey.



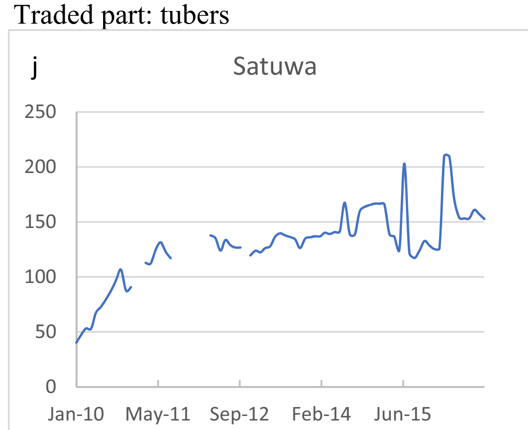
Picrorhiza scrophulariiflora
No. observations 44 (43 wild, 1 cultivated)
Traded part: rhizomes



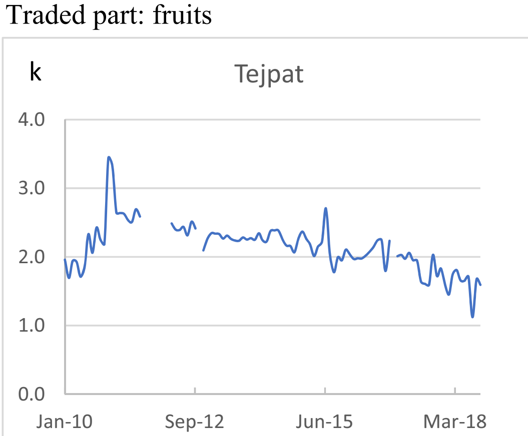
Aconitum heterophylloides, A. orochryseum, and *Delphinium denudatum*
No. observations: 18 (7 wild, 11 cultivated)
Traded part: tubers



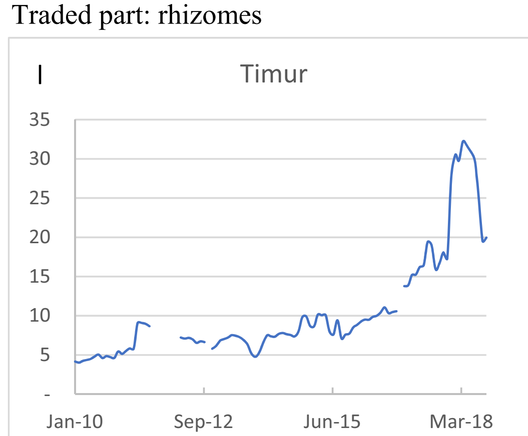
Sapindus mukorossi
No. observations: 30 (3 wild, 27 cultivated)
Traded part: fruits



Trillium govanianum and *Paris polyphylla*
No. observations: 12, all wild
Traded part: rhizomes



Cinnamomum tamala
No. observations: 79, all cultivate, 1 both
Traded part: leaves



Zanthoxylum armatum
No. observations: 24 (1 wild, 23 cultivated)
Traded part: fruits

Fig. 4a-. (*continued*).

4. Some species of fungi may represent important exceptional cases as indicated by the morel findings of the Nepalese case study, allowing continued wild harvesting at high prices. This situation may also exist for the most valuable environmental product from Nepal, the caterpillar fungus *O. sinensis* (Pouliot et al., 2018): prices have increased rapidly in the past two decades (Cunningham and Long, 2019) without proof of overexploitation (Smith-Hall and Bennike, 2022).

The econometric analysis (section 3.4.1) established strong associations between harvester characteristics and cultivation, underlining the importance of harvester factors as proposed in the new model (Fig. 3). The results do not indicate causality, e.g. it is unclear whether harvesters first decide to engage in cultivation and then choose what to cultivate, or whether it is specific products that lead to the decision to cultivate. Nor is unobserved heterogeneity ruled out leading to potential bias, e.g., if omitted harvester factors explaining the mode of harvest, such as experience, also influence the choice of products. Willingness to wild harvest might be higher among women and poorer households (as confirmed in Table 3) due to fewer alternative options, while those who choose to cultivate might decide between medicinal plant and traditional agricultural crop production depending on the availability of technology, land, labour, and capital. Cultivation can also be pursued by households who have not been engaged in prior wild harvesting (Williams et al., 2014). Additionally, geographical location influences decisions to cultivate, reflecting resource distribution. In the Nepalese case, more abundant accessible medicinal plant resources in the mountains compared with the lowlands were reflected in the significantly lower probability of harvesters cultivating in the mountains (Table 3). The revised model can be used to design more targeted surveys and data collection. For further research, multi-location, multi-product structured household surveys would be valuable, including all key variables, such as land assets, combined with qualitative in-depth analysis of local-level processes of cultivation, delving into how cultivation decisions are made and implemented. Longitudinal data collection could further improve the analysis of decision making. For instance, the change of status of a plant species from being protected or non-protected and previous harvester experience in cultivation might influence the decision to cultivate a product.

Environmental income is not a poverty trap (Walelign et al., 2020) but nor does such income provide a general pathway out of poverty (Smith-Hall et al., 2022). There are, however, examples of environmental products allowing rural households to escape poverty, including the case of wild harvested medicinal plants in Nepal (Timmermann and Smith-Hall, 2019). The present investigation of the dynamics of environmental product cultivation pathways indicates that the poverty alleviation potential of medicinal plants varies across species, harvesters, and contexts. Poverty reduction investments should focus on species where increasing prices and scarcity do not result in initiation of cultivation, indicating the need for intervention and the simultaneous achievement of conservation outcomes. There is no need for public investment in species that are abundant (either cultivation technology is established bottom-up or wild harvesting continues without threatening populations). However, as the poorest harvesters and females were more likely to engage in wild harvesting, and as they are less likely to have access to land for cultivation, poverty reduction through investment in cultivation technology is likely to primarily benefit the less poor. Reaching the poorest would require making wild harvesting more remunerative, e.g. through decreased royalties or promotion of decentralised resource management.

5. Conclusions

We developed a theoretical model of the economic dynamics of environmental product cultivation based on a systematic literature review of Homma's (1992, 1996) model of the extractive economy of the Amazon. We identified contextual (e.g., infrastructure) and mediating (e.g., cultivation technology) factors to be included in the model and included harvesters as decision makers. We identified four possible product-level outcomes: scarcity induced cultivation, economic extinction, abundance with cultivation, and abundance with continued sole wild harvesting. Our empirical test of the model, the case of commercial medicinal plant harvesting in Nepal, showed that harvester characteristics are significant for whether cultivation is undertaken or not. We also identified examples of each of the four possible outcomes. Supporting the prediction of the model, several products were cultivated despite not being documented as scarce, contradicting Homma's (1992, 1996) emphasis on resource scarcity as the main cultivation driver. Future research would allow a more detailed understanding of the model outcomes if focused on (i) the contextual factors driving price fluctuations, with particular attention on demand drivers, and (ii) how harvesters make cultivation decisions. This could help in designing poverty alleviation and conservation policies considering harvesters' actual behaviour and the influence of contextual and mediating factors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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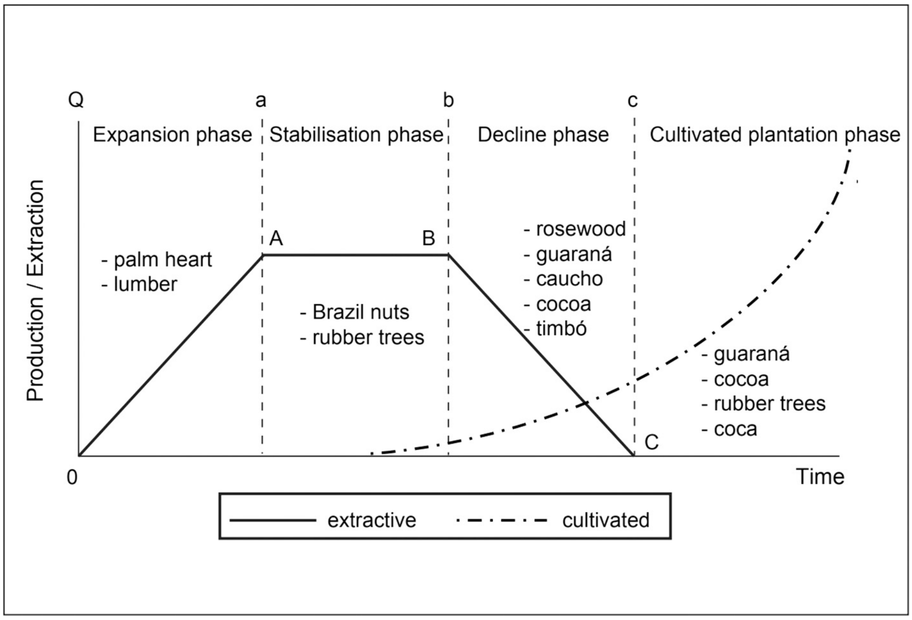
Appendix A

Homma's (1992, 1996) model illustration the phases of environmental product extraction. Figure caption in Homma (1992, 1996): ***The historical cycle of forest production in Amazonia***



Source: Homma (1996: 61).

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